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IMPLEMENTATION AND EVALUATION OF A HAPTIC PLAYBACK SYSTEM

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ABSTRACT

This article presents implementation and evaluation of a haptic playback system using the PHANToM haptic interface, in the context of our Virtual Haptic Back Project at Ohio University. Playback has the potential to improve virtual palpatory diagnosis training by allowing students to follow and feel an expert's motions prior to performing their own palpatory tasks.

We have two modes in our playback system. In mode 1 the human is passive and experiences position playback of the expert's tactile examination via the PHANToM with a PD position controller. No haptics model is enabled in mode 1. In mode 2 the human traces the expert's path actively through visual cues. Mode 2 enables the haptics model so that the trainee feels approximately what the expert did in the original task. The experiment described in this article showed that performance with playback mode 2 is enhanced (i.e. there is less position error) when preceded by playback mode 1.

1. INTRODUCTION

From the very beginnings of medicine, palpation (diagnosis through touch) has been an important part of the diagnostic process, for such things as organomegaly, the cardiac impulse, thoracic crepitus and fremitus, presence of masses (tumors) or herniations, and the presence of tenderness and edema. Palpation has been an additionally significant part of osteopathic medical practice, because of its emphasis on somatic dysfunction and viscerosomatic reflexes. Palpation is an effective, sensitive, and economical way to diagnose many musculoskeletal (somatic) dysfunctions, including those that arise from visceral abnormalities via viscerosomatic reflexes.

Unfortunately, clinically relevant palpatory diagnosis is difficult to learn. In the teaching lab students learn by palpating each other, but young, healthy students often exhibit no prominent dysfunctions. Palpation of human subjects often causes changes in the tissue being palpated, making it impossible for a group of students to palpate the same thing. Finally, the sense of touch is not a sensory modality that is well developed in most people. Virtual reality with haptic feedback shows promise for overcoming these obstacles in palpatory training.

Haptics has been applied recently to education and training, most notably in the medical field. In the Stanford Visible Female project (Heinrichs, et al., 2000), a 3D stereoscopic visualization of the female pelvis has been developed from numerous slices of 2D pelvis data. Haptic feedback was enabled via the PHANToM haptic interface, allowing the user to interact with and feel the virtual model. The Interventional Cardiology Training Simulator (Shaffer et al., 1999) links technical simulation with specific medical education content. A virtual reality-based simulator prototype for the diagnosis of prostate cancer has been developed using the PHANToM haptic interface (Burdea et al., 1999). The same research group is developing a force-feedback glove (Bouzit et al., 2002). Another tumor palpation virtual reality (VR) simulation was developed by Langrana (1997). The Immersion Corporation (www.immersion.com) has developed haptic interfaces for injection training and sinus surgery simulation. Delingette (1998) is working on realism in modeling human tissue for medical purposes. The SPIDAR haptic interface has been adapted to serve as "the next generation education system" (Cai et al., 1997), though the authors do not elaborate on the type of education intended. Basdogan et al. (2001) simulate a surgical catheter procedure using a pair of laparoscopic forceps with haptic feedback for medical training. Tendick et al. (2000) use a virtual environment including a 4-dof haptic interface for minimally-invasive surgical training. Georgetown University Medical School is developing a spine biopsy simulator for surgical training, including a PHANToM haptic interface and a physical model (Cleary et al., 1997). An example of injection simulators with haptics is presented by Dang et al. (2001).

Adams, Klowden, and Hannaford (2001) have shown a significant improvement in subject performance in a real-world Lego assembly task with VR training including force feedback. A group at the University of Ioannina in Greece is involved with virtual learning environments including a Power Glove with tactile feedback to "build a theoretical model for virtual learning environments, expanding constructivism and combining it with experiential learning" (Mikropoulos and Nikolou, 1996). A research group at the Ohio Supercomputing Center has applied haptics in virtual environments to improve tractor safety by training young rural drivers (Stredney et al., 1998); their results show haptics increases training effectiveness. Haptics has been applied to make virtual environments accessible to blind persons (Jansson et al., 1999). Affordable haptic interfaces have been implemented to augment the teaching and learning of high school physics (Williams et al., 2002). Also, the effectiveness of virtual reality (without haptics) has been demonstrated in the learning process (North, 1996).

The Virtual Haptic Back is under development at Ohio University to augment the palpatory training of osteopathic medical students and physical therapy and massage therapy students (Williams et al., 2003; Holland et al., 2002). This project has implemented a combined graphical and haptic model of a live human back on a PC, using the PHANToM interface for haptic feedback.

We have developed a playback system in the PHANToM haptic interface software environment wherein the motions of an expert may be recorded and saved for later 'playback' to trainees using the same virtual reality system. Other research groups have been including a playback feature in their work. In the aforementioned prostate tumor diagnosis work (Burdea et al., 1999), a PHANToM playback mode is used both to analyze a trainee's performance and to show the trainee how an expert approaches prostate examinations. The same research group is applying general graphics playback in palpation training for detecting subsurface tumors (Dinsmore et al., 1997); a data file is written with all inputs from all I/O devices to replay the user's actions graphically; this case does not involve the PHANToM with haptic playback. A second group is using a PHANToM playback feature in their horse ovary palpation simulator (Crossan et al., 2000), to implement a tutor/trainee model. Reachin Technologies (www.reachin.se) has developed a VR-based laparoscopic surgery trainer with haptics; this system allows recording of the simulator positions at all times so an instructor may rate the performance of students later. Weghorst et al. (1997) evaluate the Lockheed-Martin sinus simulator, developed with haptics by Immersion Corp.; that evaluation used playback of videos from the various levels of sinus surgery simulation as part of their data.

The current article focuses on the implementation and evaluation of our PHANToM playback system, motivated by training needs in the Virtual Haptic Back Project at Ohio University. Research groups using playback do not tend to give details about their playback implementations in the literature to date.

There are two modes in our playback system. In the first mode, position playback of the expert's recorded path is done using the PHANToM motors, a proportional-derivative (PD) position controller, and the trainee's finger is passive in the PHANToM thimble. This gives position playback of the expert's path, but no haptics playback since the PHANToM motors are fully occupied with the PD controller. In mode 2, a ball traces the expert's path shown in the graphics screen and the user must actively follow the ball in all three dimension to provide position playback. Mode 2 enables haptic feedback since the motors are no longer required to generate position playback. If the user follows the path with minimal error, she/he feels approximately what the expert felt during the simulated palpatory examination. Even with some haptic error due to small position playback errors and differences in physiology and approach between the trainees and expert, we believe our playback approach may have virtual palpatory training benefits.

In this article we give a brief overview of the Virtual Haptic Back Project, followed by a description of our PHANToM playback system, and then presentation and discussion of our playback system experiments and results.

2. THE VIRTUAL HAPTIC BACK

This section presents a brief overview of the Virtual Haptic Back Project at Ohio University. It concludes with a discussion of our perceived need for playback to augment virtual training effectiveness.

2.1 Virtual Haptic Back Overview

This sub-section presents a brief overview of the Virtual Haptic Back (VHB) Project at Ohio University (for more information please see Williams et al., 2003 and Holland et al., 2002). The VHB model has been under development for three years, initially funded by the Ohio University 1804 Research Fund, and now funded by the Osteopathic Heritage Foundation. The purpose of our project is to develop a series of computer-based haptic simulations of the human body to assist students in learning palpatory techniques. Our goal is to add a measurable, repeatable component of science to the art of palpatory diagnosis. Continuous evaluations by osteopathic and control student groups, plus on-going evaluations by practicing and teaching osteopathic physicians, are used for VHB improvements to ensure maximum realism and utility. We now describe the VHB model that was used in the experiment of the current article.

As shown in Figure 1, a graphics model of a human back has been developed based on measurements taken from a human subject with a 3D digitizer. Haptic feedback has been programmed for this virtual live back model via the PHANToM haptic interface (Figure 2, Massie and Salisbury, 1994, also www.sensable.com). The feel consists of linear springs of varying spring stiffnesses, normal to each of the polygons forming the surface of the back. The operator inserts a finger into the gimbaled thimble at the end of the mechanical arm of the PHANToM haptic interface. By moving this manipulandum in 3D space, the operator moves a cursor (sphere to the left in Figure 1) on the graphics screen portraying a 3D image of the back and its underlying vertebrae. As the cursor is moved against an object, such as the skin of the back, the operator feels resistance to movement of the manipulandum, and thus the user's finger receives the sense of touch from the virtual model.

Our haptic model allows the student to feel different layers of haptic feedback (i.e. palpate through the fleshy material to feel the vertebrae beneath the surface). The VHB includes a model of the spine, composed of simple representations for the spinous and transverse processes, and allowing for relative motions (6-dof translations and rotations, intended to represent the real human back). Different stiffnesses of rotation can be programmed for each spine element, allowing us to program somatic dysfunction for the student to diagnose in the virtual model. As the skin is compressed the operator first encounters resistance from compression of the skin and then additional resistances representing underlying bone. In this way the operator can palpate vertebral spinous processes C2, plus C6 through L5. The interspinous ligaments joining the spinous processes are palpated as objects with less intrinsic stiffness (more give) than the spinous processes. Transverse processes can also be palpated lateral to the spinous processes and deeper. Each vertebra can rotate in response to pressure applied by the operator to the transverse processes. The resistance to rotation can be set independently for each vertebra. The initial position of each vertebra can also be set independently via pull-down menu. The graphics can be set to reveal the underlying bone or not, so that the palpation can be done with or without the aid of seeing the underlying vertebrae on the screen (the real world does not allow this choice!). The VHB model runs on a 900MHz dual processor computer with 1 GB RAM, a 64 MB NVIDIA AGP graphics card, and Windows NT.

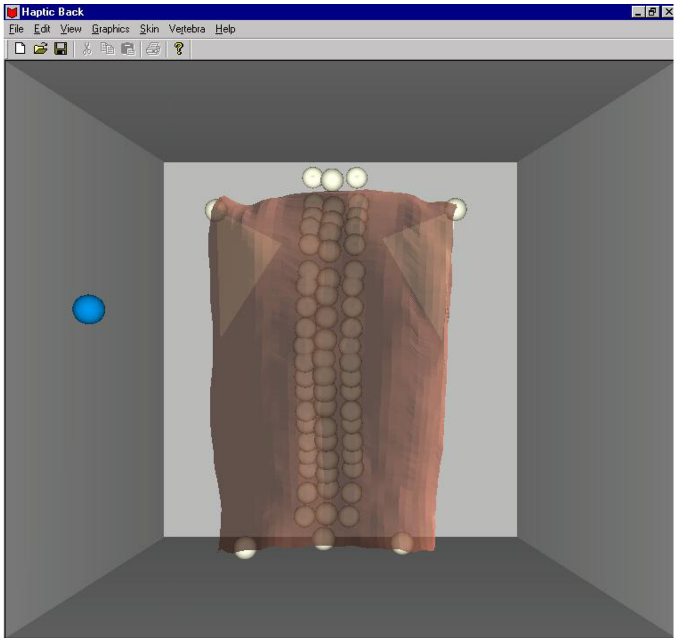

Figure 1. Virtual Haptic Back Model

Figure 2. PHANToM Haptic Interface

Our VHB model includes the major skeletal landmarks for increased realism. The circles located laterally represent the acromeon process above and the posterior superior iliac spine below. The values for spring stiffnesses for the skin and bone models, plus the rotational stiffnesses for the vertebrae were not measured from a live human subject. Rather, they were set by the development team according to subjective feel. We have been updating these values based on expert feedback.

We have made improvements upon the VHB model of Figure 1, including the use of two large PHANToMs for dual-handed palpation, the inclusion of ribs, scaling for real-world size, and more realism for vertebral graphics. However, these are not shown since Figure 1 was the model used in the playback experiments of this article. Our Virtual Haptic Back website is:

http://www.ent.ohiou.edu/~bobw/html/VHB.html

Future training evaluation using the Virtual Haptic Back will involve somatic dysfunction. The goal is to provide realistic somatic dysfunction for the trainee to identify through palpation with the virtual model; this can be done in a repeatable manner, with as much practice as the trainee desires.

2.2 Playback for Training Augmentation

As mentioned earlier we have developed a two-mode playback system for training augmentation. We believe that our PHANToM playback capabilities could have a significant impact on improving teaching and learning effectiveness in palpatory training with the Virtual Haptic Back. We plan to use our two-mode playback system in at least two ways for palpatory training. First, in an attempt to improve learning, the motions of an expert physician diagnosing somatic dysfunction with the Virtual Haptic Back can be recorded and played back using both modes and the students can practice and appreciate how an expert approaches certain palpatory problems. Second, a physician or other instructor can evaluate their students' progress by playing back individual tests with the Virtual Haptic Back. This would provide data regarding the trainee's performance, including documentation of any improvement as the training progress. This will add a quantitative evaluation component to the art of palpatory diagnosis. Of course, with a large number of students, detailed playback of every student's individual tests may be prohibitive in terms of time. Thus, our system will also give instructors the option to view and track summary statistics revealing the performance and progress of all students.

We have implemented PHANToM playback capabilities in the Virtual Haptic Back. The purpose of this article is to describe our implementation and evaluation of our playback system with human subjects.

3. TWO-MODE PLAYBACK SYSTEM

The purpose of playback is to give repetitive virtual training to the students based on an expert's interaction with the virtual simulation. For training purposes, it may be advantageous to save an expert's motions and tactile probing, so that students can experience these later. Recording the movements of an experienced physician and playing them back to a student allows the student to experience the look and feel of various tactile examinations.

Since it is not possible to develop a haptic playback system that can exactly reproduce an experts' position and force interactions simultaneously with a haptic model, we have developed a two-mode playback system approach. The first mode replays position using the haptic interface and a PD controller; this helps the passive user to experience the expert's path, but does not include any haptic feedback. The second mode requires active following by the student of the expert's path via visual cues; it helps the student to appreciate the tactile examination, including the approximate haptic interactions that the expert experienced.

It is impossible to follow a prerecorded path exactly but we accept this error since we believe that our PHANToM playback capabilities could significantly improve teaching and learning effectiveness in palpatory training with the Virtual Haptic Back. This section describes the implementation of our two-mode playback system.

To achieve playback, a data file is recorded during the expert's motions. This file records the *XYZ* positions of the PHANToM. In the original simulation the position input comes from the expert's hand/finger motions, read via the PHANToM encoders.

Mode 1

In mode 1 the user is passive. The user puts her/his finger in the thimble and the PHANToM traces the expert's path. We have implemented a PD controller for this mode 1 passive position playback. No haptics mode is allowed in playback mode 1 since the PHANToM motors are already devoted to the PD position controller.

The expert's *XYZ* positions are read and the PHANToM playback force field, *F*, to play back these positions is calculated using the PD controller of (1):

$$\mathbf{F} = K_P\mathbf{e} + K_D\frac{\Delta\mathbf{e}}{\Delta t} \tag{1}$$

where:

$$\mathbf{e} = \mathbf{X}_{pb} - \mathbf{X}_{ex} \qquad \Delta\mathbf{e} = \Delta\mathbf{X}_{pb} - \Delta\mathbf{X}_{ex}$$

The subscript *pb* indicates playback position, while *ex* represents the expert's position. The gain K_P is a virtual spring to pull the PHANToM thimble to the desired expert's position at all times, and the gain K_D is a virtual damper for better stability. Note that (1) is a three-dimensional vector equation, but we found that identical scalar gains were sufficient for the *X*, *Y*, and *Z* directions. **X** represents position vectors $\{X \quad Y \quad Z\}^T$ and **F** represents Cartesian force vectors $\{F_X \quad F_Y \quad F_Z\}^T$.

We determined the gain values K_P and K_D by trial-and-error. K_D was initially set to zero and K_P was increased until the passive playback performed well. K_D was then increased from zero until further increase introduced buzzing. The gains were found to be $K_P = 0.38$ *N/mm* and $K_D = 0.15$ *N-sec/mm*.

The force field and the PHANToM tip are initially located at the initial expert path point. The force field center is then shifted to the next recorded position. As this is done a driving force (1) acts on the PHANToM. The force field is shifted to next recorded position and this loop repeats at a rate of 1000 *Hz*. In this manner PHANToM plays back the recorded path. $\mathbf{e}$ and $\Delta\mathbf{e}$ are variable vectors which change as the PHANToM tip approaches the next point. For recording the trainee's path for later comparison with the expert's path, points are again sampled at a rate of 1000 *Hz*. Again, no haptic feedback is allowed in mode 1 since the PHANToM motors are occupied only with PD position control.

Mode 2

In the second playback mode the trainee must actively provide the playback position (she/he is not passive as in mode 1; there is no PD position controller). In mode 2 a target ball (green) traces the recorded expert's path and the user has to follow it in all three dimensions (see Figure 3, where the error is exaggerated for clarity). The *XYZ* coordinates are read from the recorded position file and the target ball traces the points. In Figure 3, *X* is horizontal to the right, *Y* is vertical up, and *Z* is normal to the page, out. To help the trainee play back the *Z* component (depth into back), a rectangular bar is used, which increases in length if the position error in the *Z* direction increases.

Mode 2 helps the trainee to feel the tactile examination that the expert did since the haptics model is enabled while the trainee is providing the position playback. If the user is able to match the target ball in the *XYZ* directions over all motion, then she/he would feel approximately what the expert had felt. The feel cannot be exact due to small position errors upon active playback; no student can reproduce the expert's motion with zero error. Even if zero position errors were possible, the feel could still vary due to differences in the expert's and trainees' physiologies and approach to the Virtual Haptic Back. However, we believe the haptic feel will be close and thus may have the potential to significantly improve our virtual palpatory training.

User positions and forces are recorded during mode 2 playback trials. Section 4 presents an experiment to evaluate our mode 2 playback method, with and without prior playback mode 1 training.

4. PLAYBACK EVALUTION RESULTS

This section presents the playback experiments and the results obtained. Two different groups participated, with ten subjects each. One group was trained with playback mode 1 (passive) before being tested on the playback mode 2 (active); the other group was not given any training prior to being tested on mode 2. The primary goal of this experiment was to test objectively whether the group that is trained with mode 1 performs better (i.e. smaller position error) than the group with no mode 1 training, when both groups are tested with active playback mode 2. The secondary goal of this experiment is to ascertain if repeated exposure to both playback modes makes subjects more familiar and comfortable with the VHB model.

4.1 Playback Experiments

For the playback experiments we recorded an 'expert' path of approximately 75 seconds (75,452 path points at 1000 *Hz*; the 'expert' was the second author). The path was made to interact with the virtual human skin, spine, interspinous ligaments, and the scapula.

Position Errors. The differences between the recorded position from the expert and those obtained during playback are calculated in the *X*, *Y*, *Z* directions. In this article, a mean square error (*MSE*) measure is used for position errors:

$$MSE = \frac{\sum_{i=1}^{n} \sqrt{(X_{iR} - X_{iP})^2 + (Y_{iR} - Y_{iP})^2 + (Z_{iR} - Z_{iP})^2}}{n} \qquad (2)$$

X_{iR} is the recorded and X_{iP} the played-back *X* component of position at the i^{th} point; the *Y* and *Z* terms are defined in a similar manner. This error measure is calculated for the entire set of points, summed as shown in (2), and divided by the total number of sampled points *n* to obtain the MSE.

While playback is performed in mode 2, i.e. the user is actively trying to follow the expert's path through visual cues, the positions of the PHANToM are compared with the recorded positions and the mean square error is calculated. Each subject was asked to follow the same expert's path seven times.

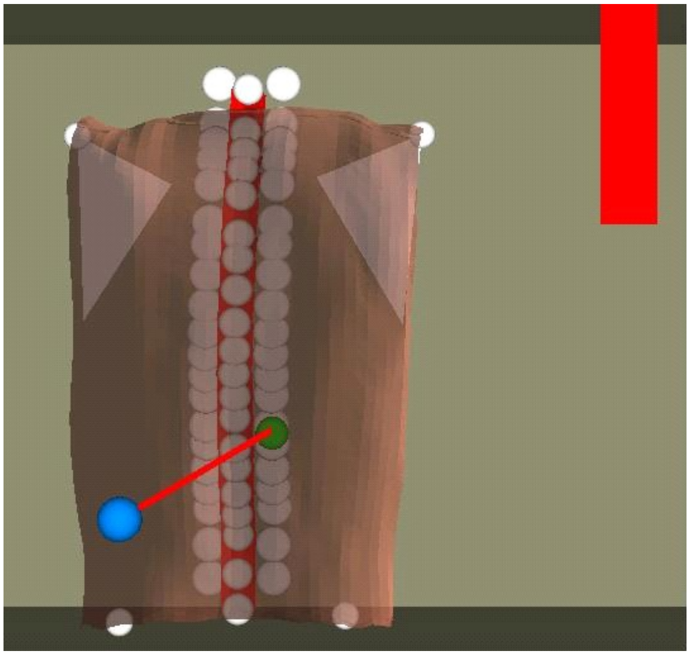

Figure 3. Active Mode 2 with Target Ball and *Z* Error Bar

Experiment description:

Twenty subjects were randomly assigned into two groups of ten subjects each. Group one used mode 1 (passive) practice and mode 2 (active) with data collection, alternately for seven trials. Group 2 used mode 2 (active) with data collection only, for seven trials.

In Figure 4 the average mean square error (MSE) of each trial is plotted against the trial number. Each point in Figure 4 is the average over ten subjects' MSE (see (2), our measure of playback position error from the expert's path) for a specific trial. The standard error bars are also shown in Figure 4, to indicate the variance in the MSE results.

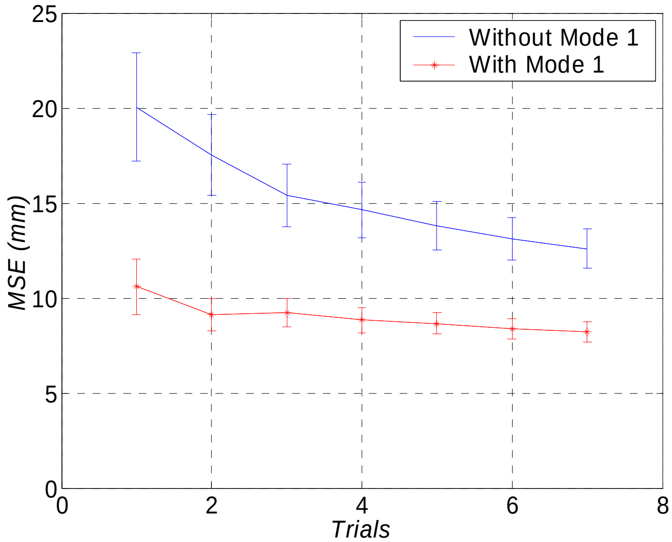

Figure 4. Playback Evaluation Results

4.2 Discussion

From the Figure 4 results we see that users generally improve in tracking the expert's path with repeated trials (the group without passive mode 1 playback training improved at a higher rate). Considering both treatment groups independently, the reduction of position errors over subsequent trials indicates that both playback modes are helping to make the trainee more familiar and comfortable with the VHB. This demonstrates success in our secondary goal.

We also see that the group that was trained using the passive playback mode 1 (mode) performed much better, with regard to lower position MSEs, than the group without this passive playback training. Further, the MSE variance in the group with mode 1 training is lower than that of the other group. This demonstrates success in our primary goal for this experiment.

The design of our experiment could have been better since Group 2 (Mode 2 only) only used the simulation half as much as Group 1 (Mode 1 training followed by Mode 2). One could thus argue that the improvement shown by Group 1 compared to Group 2 (Figure 4) is only due to more experience with the VHB. However, if this were the only explanation, then by Trial 2 Group 2 should match the Group 1 Trial 1 performance, by Trial 4 Group 2 should match the Group 1 Trial 2 performance, and so on. We see from Figure 4 that this is far from the case, i.e. after seven trials, Group 2 still has not achieved as small a position error as Group 1 did in the first trial. Thus, we can conclude that there is a component of improvement in the Group 1 performance which is not attributable to increased exposure alone; we attribute this improvement to the Mode 1 training which Group 2 did not get.

To ascertain the significance of our results (to test whether the differences between treatment groups in the average Figure 4 MSEs are statistically significant), the Figure 4 data was analyzed using SPSS via a repeated measures analysis of variance (RMANOVA) with trial as the repeated measure. The significance level was set at $P < 0.05$. Due to considerations of sphericity of the data, post hoc analysis was done with multiple t-tests, using the Bonferroni correction. There was a significant difference between groups 1 and 2 for trials 2 through 7. In the first trial, the difference between the two groups just missed significance (P = .056). In Figure 4, the first trial appears to have the greatest difference between Group 1 and 2 performance; however, the lack of significance is due to the fact that Trial 1 also has the largest error bars as well. This is a very conservative significance measure and the first trial just barely missed significance; for all intents and purposes all seven trials exhibit a significant difference.

From our results we conclude that the passive mode 1 playback training is beneficial to lower-position-error trainee performance in tracking an expert's path during an example palpatory diagnosis task via active playback mode 2. Now, the question for our experiments in the near future is "Does the active playback mode 2 (complete with passive mode 1 training) improve the trainees' performance with regard to palpatory diagnosis with the Virtual Haptic Back?" This, then, begs the further question "Does practice with the Virtual Haptic Back (including modes 1 and 2 playback training) improve trainees' palpatory diagnosis skills with real patients?" So, we will have many happy hours in the lab to address these questions.

4.3 Mode 1 Position Playback Evaluation

The position MSEs and standard error bars of Figure 4 help in showing how faithful the overall mode 2 active position playback is. But we have not yet considered mode 1 passive playback errors. In Figure 5, the red curve represents the recorded positions and the green curve shows the path traced by the PHANToM in an example mode 1 position playback (performed passively by the expert who generated the test path for the mode 2 experiments of Sections 4.1 and 4.2; the same path is used in Figure 5). For black & white printouts of this article, the solid red path is darker than the green path in Figure 5. It was observed that the two lines were close throughout the entire motion, so the position error is fairly evenly spread. Over several trials, the expert generally experienced mode 1 passive position playback errors $MSE < 4$ mm; the lowest error recorded was $MSE = 0.264$. This indicates that the mode 1 PD position controller is performing well with regard to position error, generally much better than can be expected from the mode 2 position playback provided by the subjects actively following the expert's path (see Figure 4). Of course, the higher error of mode 2 may justified considering haptics is enabled for mode 2, while haptics is not enabled for mode 1.

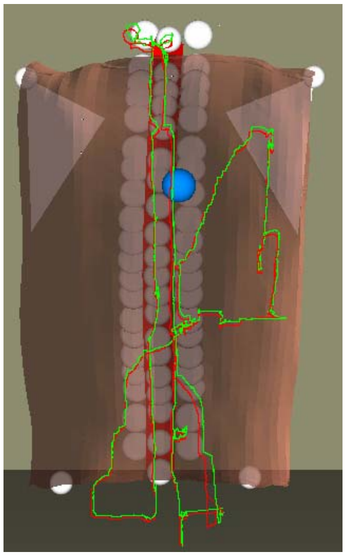

Figure 5. Playback and Recorded Paths

5. CONCLUSION

This article has presented implementation and evaluation of our two-mode PHANToM haptic interface playback system, for osteopathic medical student training in our Virtual Haptic Back (VHB) Project at Ohio University. Playback mode 1 uses a PD controller to cause the user's finger to trace out the path of an earlier-recorded expert's motions during example palpatory diagnoses. Mode 1 is called passive since the trainee's finger is passive (while the system is actively replaying position). In mode 1 there is no haptic feedback since the haptic interface motors are already used to play back position. Playback mode 2 uses graphical cues for the trainee to actively follow, replicating the recorded expert's motions via trainee arm, hand, and finger motions. In mode 2 the VHB haptics model is enabled (since the haptic interface motors are now free to be used) and the trainee feels approximately what the expert felt during the recorded motion. We are investigating whether our two-mode playback system is beneficial in palpatory training applications.

The experiment presented in this article tested whether playback training with passive mode 1 improves performance during active playback mode 2 trials. Our results show that the group with passive mode 1 training performed significantly better (with regard to lower playback position errors) than the group without passive mode 1 training. Therefore, in our future work in this area (testing if playback improves performance with the Virtual Haptic Back and then whether practice with the Virtual Haptic Back improves palpatory diagnosis performance with real patients), we will use both playback modes for the groups that use playback in their experiences.

We believe that our two-mode playback system can significantly improve virtual training applications based on this first step in implementation and evaluation.

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